

EXCITATION FUNCTIONS DERIVED FROM PROTON  
AND  
DEUTERON MEASUREMENTS ON NATURAL CHROMIUM

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EXCITATION FUNCTIONS DERIVED FROM PROTON AND DEUTERON MEASUREMENTS  
ON NATURAL CHROMIUM

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As a part of a program to measure charged-particle nuclear reactions of interest to Test Program, we earlier reported measurements of the  $^{48}\text{Ti}(p,n)^{48}\text{V}$ ,  $^{47}\text{Ti}(d,n)^{48}\text{V}$  and  $^{48}\text{Ti}(d,2n)^{48}\text{V}$  excitation functions. Here we report measurements of the  $^{52}\text{Cr}(p,n)^{52}\text{Mn}$ ,  $^{52}\text{Cr}(d,2n)^{52}\text{Mn}$ , and  $^{50}\text{Cr}(d,\alpha)^{48}\text{V}$  excitation functions obtained from targets of natural chromium. These data will become part of the LLNL data base.

Natural chromium consists of  $^{50}\text{Cr}(4.345\%)$ ,  $^{52}\text{Cr}(83.789\%)$ ,  $^{53}\text{Cr}(9.501\%)$ , and  $^{54}\text{Cr}(2.365\%)$ . The targets consisted of pure aluminum foils 1.0 mil thick by 1.0 in. diameter evaporated with chromium to a density of 0.3 to 6.0 mg/cm<sup>2</sup> by the Material Fabrication Division at LLNL. For those foils with density greater than 1.3 mg/cm<sup>2</sup>, the coating was evenly distributed on both sides of the aluminum foil to prevent curling. Irradiations were carried out at the LLNL Cyclograaff using protons up to 27 MeV and deuterons up to 20 MeV. Some irradiations were done using stacked foils, interspersed with aluminum as energy degraders, and some with single foils. In all cases aluminum catcher foils were used to catch those product ions that recoiled out of the back of the chromium foils. The activities produced in the chromium and catcher foils were counted on the germanium detectors in Building 151, and the resultant spectra were analyzed using the code GAMANAL.<sup>1</sup>

$^{52}\text{Mn}$  is produced in two forms: the 2<sup>+</sup> isomer at 378 keV above the ground state and the 6<sup>+</sup> ground state. The isomer decays to  $^{52}\text{Cr}(0^+)$  with a 21.0 min half-life and the ground state decays with a 5.59 d half-life. We have obtained data for both lifetimes produced by proton and deuteron irradiations. The isomer studies provide a sensitive test of nuclear models

and reaction mechanisms. Some preliminary results are reported in the Nuclear Chemistry Division FY85 Annual Report.<sup>2</sup> We do not mention them further here since only the ground state results are of direct interest to Test Program.

The  $^{52}\text{Cr}(p,n)^{52}\text{gMn}$  excitation function is given in Table 1. Threshold for the reaction is  $E_{\text{lab}} = 5.60$  MeV. Above  $E_{\text{lab}} = 13.68$  MeV, the data has a small contribution from the  $^{53}\text{Cr}(p,2n)^{52}\text{gMn}$  reaction. ALICE<sup>3</sup> code indicates a peak contribution at 22 to 24 MeV. If the  $2^+/6^+$  isomeric production is one to one at this energy, the contribution to the excitation function is  $\sim 5$  mb. The first column in Table 1, the run number, is the day of the year. The consistency of the data, which were collected on widely separated days, provides a measure of confidence. Column 2 gives the range of energies in the foil, calculated without straggling. Here, double-sided foils were used. The effective energies of the protons in the double foils were close in value to the extremes represented by  $\Delta E$ ; the distribution peaked at  $E_{\text{lab}} \pm (\Delta E/2 - 0.040)$ . The first two energies in column 3 required small corrections for this aspect of the experiment. In the mode in which we were using the Cyclograaff, energies should be known to  $\pm 0.01$  MeV for  $E \leq 12$  MeV (Van de Graaff only) and  $\pm 0.020$  MeV above that energy. However, the analysis of data obtained in the rising portion of the excitation function would indicate that we should probably use  $\pm 0.020$  MeV at all energies. The fourth column gives the cross section for populating the ground state of  $^{52}\text{Mn}$ . The counting statistics for these data were less than 1%, usually  $\sim 0.6\%$ . However, the systematic error that can be expected in the counting system is  $\pm 2\%$  (Gunnink, private communication, 1985), which limits the accuracy of the final results. The coincidence summing of two or more gamma rays in time coincidence can contribute to a count-rate loss of several percent. We calculated the required correction; the uncertainty in our calculation contributed  $\sim 0.5\%$  error to the cross section. For those foils that were  $1 \text{ mg/cm}^2$  or greater, data consistency indicates that the foil thickness variations contributed little to the error of measurement. Generally, unless indicated otherwise, the error is estimated at  $\pm 3\%$ .

Table 2 gives the  $^{52}\text{Cr}(d,2n)^{52}\text{gMn}$  excitation function. Here we note in column 2 (the relatively small  $\Delta E$ ) that single-sided foils were used for energies up to 11.47 MeV. The earlier comments regarding errors etc. pertain here.

Table 3 gives the  $^{50}\text{Cr}(d,\alpha)^{48}\text{V}$  excitation function. Since the isotopic abundance of  $^{50}\text{Cr}$  is but 4.345% in natural chromium, counting statistics limited the precision in the data so that relative comparisons for the cross sections are not as good as for the other excitation functions. The errors given are our estimates of the absolute accuracy of the data.

Prior data, available in the literature, have been examined. Wing and Huizenga<sup>4</sup> have made measurements for  $^{52}\text{Cr}(p,n)^{52}\text{Mn}$  from 6 to 10.5 MeV. The agreement with our data for  $^{52}\text{Mn}$  is within experimental accuracy. However, their  $^{52}\text{Mn}$  data are -20% lower than our data at 10 MeV, indicating a possible problem in their measurements of  $^{52}\text{Mn}$ . The data of Linder and James<sup>5</sup> are only qualitatively in agreement (as much as X2 too large). It does not even help to correct for the  $\beta^+$  intensity of 35% which they used, rather than the presently accepted value of 28%. Boehm et al.<sup>6</sup> have made measurements of both  $\sigma(g)$  and  $\sigma(m)$  near threshold that agree with our data and extend the measurements to within a few keV of threshold.

Cogneau et al.<sup>7</sup> have measured  $^{52}\text{Cr}(d,2n)^{52}\text{Mn}$  from 8.6 to 11.7 MeV. They did  $\beta^+$  counting assuming a 35% decay intensity. Correcting their data by 35/28 to allow for the 28% accepted value of  $\beta^+$  intensity gives cross sections in very good agreement with ours. Burgus et al.<sup>8</sup> have provided four data points in the range 8.5 to 20 MeV which need to be increased by 35/28. Their point at 8.5 MeV is high by X6 but their other three points are higher than our data by -25%. We have not made a special search in the literature for the  $^{50}\text{Cr}(d,\alpha)^{48}\text{V}$  cross sections but are aware of no other measurements.

Figures 1, 2, and 3 show the results of our experimental measurements. We have included calculations from STAPRE<sup>9</sup> for comparison. We note that for the (p,n) reaction the agreement is much better than for the (d,2n) and (d, $\alpha$ ) reactions. More detail regarding this is given in the Nuclear Chemistry Division FY85 Annual Report<sup>2</sup>.

Figures 4 and 5 show our new (p,n) at (d,2n) results compared with the old cross section from the Nuclear Chemistry Division data base. Significant changes are noted.

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Table 1. The  $^{52}\text{Cr}(p,n)^{52}\text{Mn}$  Excitation Function

Run	$\Delta E$ (MeV)	$E_{\text{lab}}$ (MeV)	$\sigma$ (mb)
86	0.394	6.34 <sup>a</sup>	4.85
86	0.499	6.77 <sup>a</sup>	14.5
86	0.352	7.32	26.0
86	0.410	7.79	41.1
86	0.448	8.78	56.9
86	0.324	9.84	80.9
86	0.357	11.82	111.7
92	0.244	14.24	138.2
105	0.213	15.39	120.7
92	0.214	16.89	96.1
92	0.193	18.90	61.1
92	0.175	20.91	44.4
92	0.180	22.91	35.7
105	0.184	24.91	29.1
105	0.188	26.91	24.6

<sup>a</sup>Here the effective energy is not equal to the average energy in the foil. Small corrections were made to allow for non linear variation of the cross section over the range of particle energy variation  $\Delta E$ .

Table 2. The  $^{52}\text{Cr}(d,2n)^{52}\text{Mn}$  Excitation Function

Run	$\Delta E$ (MeV)	$E_{\text{lab}}$ (MeV)	$\sigma$ (52 <sup>g</sup> )	Run	$\Delta E$ (MeV)	$E_{\text{lab}}$ (MeV)	$\sigma$ (52 <sup>g</sup> )
220	0.062	8.17	$0.176 \pm 0.007$	235	0.418	13.47	141.3
220	0.062	8.27	$0.508 \pm 0.020$	114	0.45	13.78	150.1
220	0.062	8.37	$0.961 \pm 0.020$	235	0.376	15.05	169.8
192	0.081	8.46	1.84 <sup>a</sup>	114	0.360	15.82	177.2
220	0.081	8.56	2.48	298	0.35	15.89	181.6
192	0.080	8.71	4.71	235	0.45	16.91	187.0
171	0.070	8.97	7.99	298	0.336	17.66	192.9
171	0.077	9.46	17.29	114	0.40	17.80	197.2
157	0.066	9.60	25.03	235	0.174	18.25	198.5
134	0.16	9.62	20.72	298	0.350	19.32	195.5
220	0.50	9.89	31.30	235	0.407	19.58	197.0
171	0.066	9.97	34.15	133	0.370	19.82	197.6
157	0.062	10.62	58.34				
134	0.018	10.65	53.17				
171	0.062	10.97	74.61				
171	0.066	11.47	87.42				
114	0.51	11.75	100.6				
235	0.42	11.76	97.5				

<sup>a</sup>The uncertainty in the cross sections at higher energies are limited by the absolute accuracy in  $\gamma$  measurement of  $\pm 2\%$ . With the other sources of error included, these latter numbers should be considered good to  $\pm 3\%$ .

Table 3. The  $^{50}\text{Cr}(d,\alpha)^{48}\text{V}$  Excitation Function

Run	$\Delta E$ (MeV)	$E_{\text{lab}}$ (MeV)	$\sigma$ (mb)	Run	$\Delta E$ (MeV)	$E_{\text{lab}}$ (MeV)	$\sigma$ (mb)
289	0.823	4.59	$9.2 \pm 0.16$	171	0.066	11.47	$61.5 \pm 3.3$
220	0.996	4.64	$8.78 \pm 0.17$	235	0.42	11.76	$63.0 \pm 3.2$
289	0.692	5.78	$19.3 \pm 0.6$	157	0.22	12.89	$57.3 \pm 3.5$
289	0.822	6.97	$31.9 \pm 1.0$	235	0.418	13.47	$53.5 \pm 3.4$
220	0.619	7.64	$38.2 \pm 0.45$	157	0.20	14.90	$40.8 \pm 3.5$
220	0.062	8.17	$41.2 \pm 0.73$	235	0.376	15.05	$40.6 \pm 4.5$
220	0.062	8.27	$43.4 \pm 0.79$	298	0.35	15.89	$34.4 \pm 1.0$
220	0.062	8.37	$44.6 \pm 0.82$	235	0.45	16.91	$30.9 \pm 6.2$
192	0.080	8.46	$48.1 \pm 0.3$	298	0.336	17.66	$25.1 \pm 0.7$
220	0.081	8.56	$47.5 \pm 0.7$	235	0.174	18.25	$25.8 \pm 5.0$
192	0.080	8.71	$50.7 \pm 0.3$	133	0.33	18.83	$26.0 \pm 3.5$
171	0.070	8.97	$51.3 \pm 0.6$	298	0.35	19.32	$22.8 \pm 0.7$
171	0.077	9.46	$54.1 \pm 0.7$	235	0.407	19.58	$20.2 \pm 3.2$
157	0.066	9.60	$61.8 \pm 3.0$	133	0.370	19.82	$17.1 \pm 3.9$
134	0.16	9.62	$59.8 \pm 4.0$				
220	0.50	9.89	$57.8 \pm 1.4$				
171	0.062	9.97	$60.4 \pm 1.4$				
157	0.062	10.62	$64.4 \pm 3.3$				
171	0.062	10.97	$62.4 \pm 2.2$				

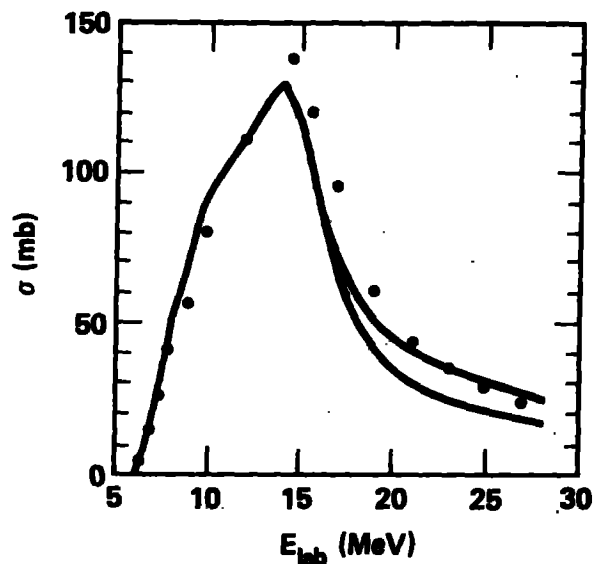


Fig. 1  $^{52}\text{Cr}(p,n)^{52}\text{Mn}$  excitation function. The dots are data and the solid curves result from calculations using the statistical-model code STAPRE with two different pre-equilibrium-model assumptions.

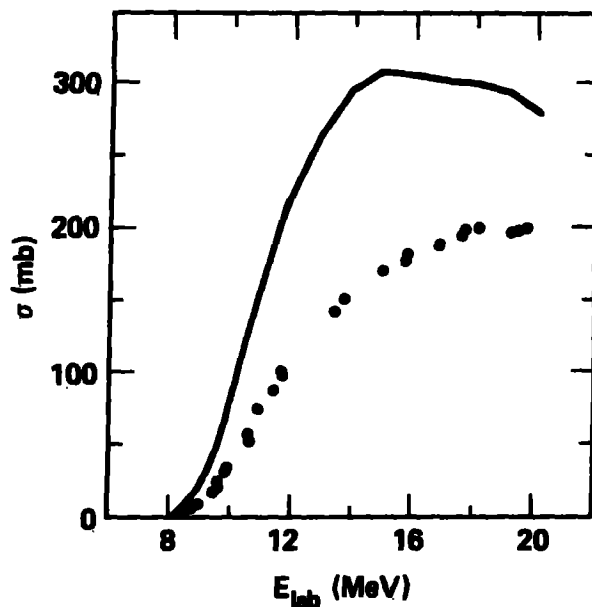


Fig. 2  $^{52}\text{Cr}(d,2n)^{52}\text{Mn}$  excitation function. The dots are data points and the solid curve STAPRE results. The larger difference is believed due to deuteron breakup in the Coulomb field of the nucleus.

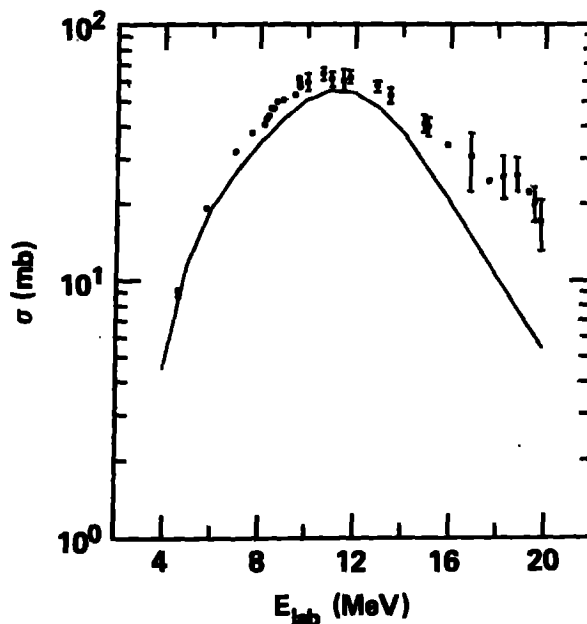


Fig. 3  $^{50}\text{Cr}(d,\alpha)^{48}\text{V}$  excitation function. The dots with error bars are data and the solid curve STAPRE results.

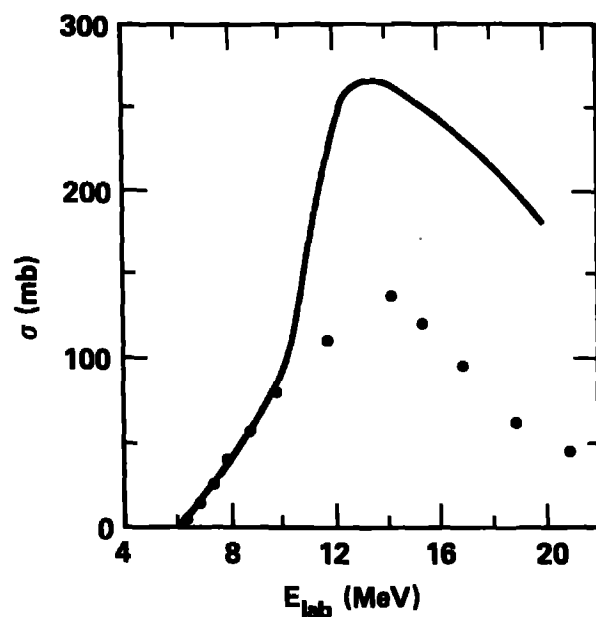


Fig. 4 Data comparison between previous data (solid curve) in use at LLNL and new data (dots). The solid curve below 10 MeV is due to Wing and Huizenga<sup>4</sup>; above ~10 MeV it is due to the questionable data of Linder and James.<sup>5</sup>

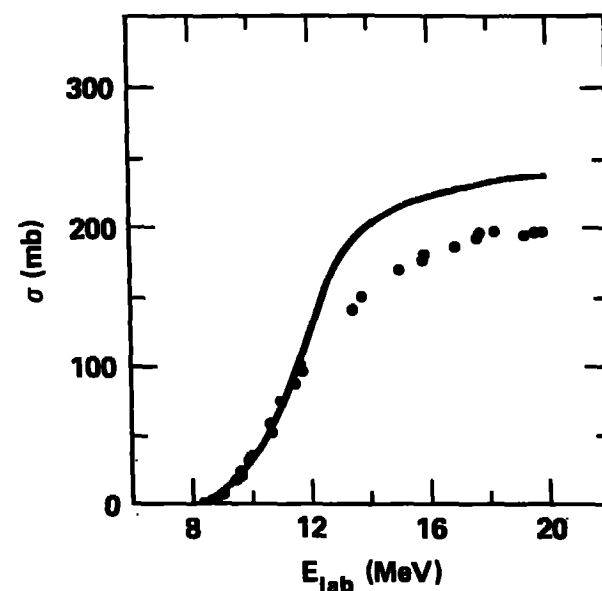


Fig. 5 Data comparison between previous data (solid curve) in use at LLNL and new data (dots). The solid curve below ~10 MeV is due to Cogneau et al.<sup>7</sup>; above ~10 MeV it is due to Burgus et al.<sup>8</sup>